



Soil organic carbon sequestration and mitigation potential in a rice cropland in Bangladesh – a modelling approach



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ABSTRACT

An increase in the storage of carbon (C) in soil by changing management practices can help to mitigate climate change and increase soil quality. The objective of this study was to evaluate the best management options for reducing greenhouse gas (GHG) emissions. An ecosystem model DayCent was tested for two rice (*Oryza sativa* L.) experimental sites in Bangladesh. The sites are under different management practices and we first tested the models ability to simulate SOC turnover, and then estimated the potential for SOC sequestration by comparing change in SOC for each management scenario with baseline management (current farmers' practices) including conventional tillage, 5% residue incorporation and nitrogen (N) fertilizer. Predicted yield was also compared at both sites to ensure that yield was not compromised by mitigation measures. A control treatment was tested at both sites. At site 1, two other treatments of mineral N fertilizer, and combination of farmyard manure (FYM) and N were tested in a double rice based crop rotation. At site 2, a treatment receiving cowdung (CD) application, and a combination of CD and N were tested in a wheat (*Triticum aestivum* L.)-rice based crop rotation. The DayCent model was able to simulate SOC increase from the double rice test sites under unfertilized conditions, considering additional N and C sources in the simulations. Assuming N fertilizer (180 kg N ha⁻¹ yr⁻¹) application for site 1, and CD application (25 t ha⁻¹ yr⁻¹) for site 2, respectively, as the baseline, four single, and one integrated, scenarios were implemented in the model to predict SOC and yield at both sites. Two additional scenarios with alternate wet and drying (AWD) as a single treatment, and as part of an integrated approach, were also tested for their mitigation potential at site 1. The highest simulated positive impact on SOC development (60% higher than that of the baseline) was observed at site 1 when FYM was used in place of mineral N fertilizer. As there is a yield penalty associated with the use of only FYM, integrated approaches might show more promise, such as inclusion of 15% residue return, reduced tillage, less mineral N fertilizer, FYM addition, with or without AWD. This approach increases SOC by up to 23% while keeping the yield stable (nearly 3.5 t ha⁻¹). The application of CD only as determined for baseline of site 2, gives a yield of about 1.8 t ha⁻¹ yr⁻¹. In contrast nearly two times more yield was obtained under the scenario associated with integrated management which also increases SOC by 30% relative to the baseline at the second site. Net GHG emissions, including nitrous oxide and methane emissions were estimated using the Intergovernmental Panel on Climate Change (IPCC) tier 1 methods, and country specific emission factors (where available), suggests that the integrated management scenario can reduce the net GHG emissions from 0.58–0.82 t carbon dioxide (CO₂)-eq. ha⁻¹ yr⁻¹ (equivalent to 0.16–0.24 t Ceq. ha⁻¹ yr⁻¹) at site 2, while a net reduction in GHGs of nearly 1.00 t CO₂-eq. ha⁻¹ yr⁻¹ (equivalent to 0.27 t Ceq. ha⁻¹ yr⁻¹) at site 1 was only achieved if AWD was also implemented with the integrated management scenario. Future studies could attempt to model non-CO₂ GHGs with a dynamic model.

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1. Introduction

Agricultural land occupies approximately 70% of the 13 million hectare (Mha) of Bangladesh, and around 80% of this agricultural land is used for arable cropping (FAOSTAT, 2017). In 2014, around 34 million tonnes (Mt) of rice (*Oryza sativa* L.) was produced in Bangladesh, which is about 7% of global rice production (BBS, 2016). Agriculture is also estimated to be one of the largest sources of greenhouse gas (GHG) emissions in Bangladesh, estimated at 75 Teragram (Tg) carbon dioxide (CO₂)-eq. in 2014, and has increased by 55% over the period 1980–2014 (FAOSTAT, 2017). Although GHG emissions from agriculture in Bangladesh account for only ~1.4% of total global emissions (FAOSTAT, 2017), it is one of the most vulnerable countries in the world to climate change, due to its socio-economic conditions and geographical location (MOEF, 2008). Meeting the demands of an increasing population through sustainable agricultural practices is, therefore, a critical challenge for Bangladesh.

Researchers and policy makers in Bangladesh have focused mostly on adaptation to climate change rather than its mitigation. For instance in Bangladesh the Climate Change Strategy and Action Plan (BCCSAP) of 2009 had six pillars, with the fifth pillar providing only a brief outline about mitigation (Hussain and Rashid, 2016). In the Nationally Determined Contribution (NDC) 2015, Bangladesh pledged to reduce GHG emissions from non-agriculture sectors and emissions from agriculture were not included due to lack of available data (Hussain and Rashid, 2016). Nationally Appropriate Mitigation Actions (NAMAs), which are defined as any action that ultimately contributes to GHG reductions whilst addressing the development needs of the country, have been developed by the government of Bangladesh (GIZ, 2013). The goal is to reduce GHG emissions from baseline projections by at least one third by 2030 (Dion et al., 2012). Three NAMAs have been identified for agriculture: a) SOC sequestration in agricultural soils, b) improved rice cropping methods and c) improved water and energy-use efficiency.

It is estimated that close to 90% of the agricultural sector's total mitigation potential could be derived from SOC sequestration, with about 10% from reduction of non-CO₂ GHGs (Smith et al., 2007). Rice management offers substantial mitigation potential (Smith et al., 2008), which has been studied recently by researchers in Asia, including India (Nayak et al., 2012; Babu et al., 2006) and China (Wang et al., 2015; Nayak et al., 2015). Under modified rice management practices, SOC could be sequestered in India and China at a rate of about 8–16 Tg C yr⁻¹ and 8–500 Tg C yr⁻¹, respectively (Lal, 2004; Xu et al., 2011). Compared to upland crops, paddy soils sequester more C due to long term reduction of microbial decomposition (Yan et al., 2013). Even in the unfertilized paddy rice fields in China, it was found that SOC increased by 13–60% in the control plot over a long term study (Yan et al., 2013; Hao et al., 2008; Tong et al., 2009). Yield also increased in unfertilized plots, and previous studies have suggest that external N sources like wet and dry deposition, microbial N fixation including photosynthetic bacteria, weeds, azolla, and blue green algae (BGA) growing in the standing water and soil water interface, contribute to N balances (Roger and Ladha, 1992; Mian et al., 1991; Pampolino et al., 2008). It is therefore necessary to further investigate the impact on SOC and yield of different management practices, including low nutrient inputs, as well as options to mitigate GHG emissions and maintain yield.

Although the mean technical mitigation potential for SOC storage under improved agricultural practices was estimated to be greater in South Asia than in either Africa or Europe (Smith et al., 2008), research on sequestration potential under different fertilization regimes in South Asian croplands, especially in Bangladesh, is scarce. In Bangladesh, two long term (over 20 years) fertilizer experiments have examined the effect of rice-based crop rotations on SOC (Karim et al., 1995; Egashira et al., 2003, 2005). However, there are still no estimates for the mitigation potential of the agricultural sector. The objective of the study, therefore, was to estimate the potential to increase soil organic carbon

stocks and to evaluate the best management options for reducing GHG emissions. Several modelling studies (using e.g. DNDC, CENTURY) have simulated SOC change and mitigation potential with rice-based cropping systems in different regions of Asia (Xu et al., 2011; Bhattacharyya et al., 2007). For this study, we selected the DayCent model (Parton et al., 1998) because it can be readily be applied to croplands (Begum et al., 2017; Senapati et al., 2016), it has been tested in the global simulation of rice growth (Stehfest et al., 2007). This modified version has recently been applied for 350 rice based datasets in China (Cheng et al., 2014). The model was parameterised with a portion of the sites in China, and independently evaluated with other sites in that dataset. The results from China provide confidence that the model provides reasonable results for estimating SOC changes in paddy rice systems. GHG mitigation potentials were also determined in Chinese rice cropland using this model (Cheng et al., 2013, 2014). The DayCent model also tested in the United Nations for its applicability for use in GHG inventories (US EPA, 2017). Quantifying the potential for mitigation climate change through SOC sequestration while maintaining yield, will help policy makers to develop strategies to ensure environmental sustainability and to meet the challenge of feeding the growing population.

2. Materials and methods

2.1. Experimental sites

Data from two experimental sites in Bangladesh were used in this study. The sites belong to the Bangladesh Agricultural University (BAU) and Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), with their details summarised in Table 1.

The first long term field experiment is on a very young floodplain soil with a yearly irrigated rice-fallow-rainfed rice cropping rotation (Kader et al., 2017). Three crops were cultivated each year during 1978–1982. Rice was grown in two seasons: *aus* (March–June) and *aman* (July–November), with a pulse sown in the dry winter season (December–February). With the availability of irrigation facilities and high yielding varieties (HYV) rice was cultivated in two growing seasons from 1983 onwards.

Three sets of plots were simulated for site 1 (S1), including no application of fertilizer or manure (control), mineral nitrogen (N) fertilizer plots (MN), and combined application of N and farmyard manure plots (FYMN), which are common practices in Bangladesh. In the MN plot, the N rate varied (~70 kg N ha⁻¹ yr⁻¹) depending on rice cultivars until 1982, but the rate was fixed at 180 kg N ha⁻¹ yr⁻¹ from 1982 onwards, when cultivation of HYV began. One-third of the N was applied just before transplanting of rice; the remaining portion was applied in two equal splits at 25–30 days and at 50–55 days after transplanting, respectively. In the FYMN plot, FYM (prepared with rice straw and cowdung, moisture content 60%, 1.1% N, with C:N ratio 27) application began in 1982, and was applied only before growth of the first irrigated rice. The N rate in the FYMN plot was half the N applied in the MN plot. The main source of water for *aman* season is rainfall which floods the soil, but irrigation water is supplied in case of insufficient rainfall, while irrigation by deep tube well is the main source of water during the *boro* season. To differentiate between the two rice seasons, irrigated rice or dry season rice is identified as R1, while rainfed rice or wet season rice is indicated by R2, respectively. Therefore, cropping seasons for S1 are indicated as S1R1 and S1R2, respectively.

The second experimental site (S2) is on a weathered terrace soil with a yearly wheat (*Triticum aestivum* L.)-fallow-rainfed rice cropping rotation. This site was established in 1988 to evaluate different manure management strategies with a control, cowdung (CD, prepared with only cowdung, moisture content around 72%, N content is 1.19% with C:N ratio 16) and a combination of CD and mineral N fertilizer (CDN), based on common management practices in the country. For wheat, half of the N fertilizer was applied during final land preparation and the rest was applied in two equal splits at 20–25 days and at 50–55 days

Table 1

Description of test site 1 (rice-rice) and site 2 (rice-wheat), in long term experiment Bangladesh, used for modelling.

	Site 1	Site 2
Site name	BAU, Mymensingh.	BSMAU, Gazipur, Dhaka.
Latitude/longitude	24°43' N, 90°25' E	24°05' N, 90°16' E
Agroecological zone (AEZ)	Young Brahmaputra floodplain (AEZ 9)	Madhupur tract (AEZ 28)
Soil taxonomy	Aeric Haplaquept	Ultic Ustocrept
Altitude (m)	8	10–12
Duration of study	1978–2015	1988–2008
Plot size	12 m X 6 m	12 m X 7 m
Texture (%)	Silt loam (19, 63 and 18% sand, silt and clay, respectively).	Silty clay loam (15, 46 and 39% sand, silt and clay, respectively)
pH	6.8 (0–15 cm depth)	5.6 (0–5 cm depth) 5.4 (10–15 cm depth) 5.3 (20–25 cm depth)
Bulk density (g cm ⁻³)	1.22 (0–15 cm depth)	1.46 (0–5 cm depth) 1.77 (10–15 cm depth) 1.69 (20–25 cm depth)
Initial SOC (%)	0.73 (0–15 cm depth)	0.41 (0–5 cm depth) 0.38 (10–15 cm depth) 0.27 (20–25 cm depth)
Cropping season	S1R1: Mid-January to mid-May S1R2: Mid-July to mid-November	S2W: Mid-November to mid-March S2R2: Mid-July to mid-November
Treatments	S1T1: S1R1Control S1R2Control S1T2: S1R1N90 S1R2N90 S1T3: S1R1FYM5N90 S1R2FYM0N90	S2T1: S2WControl S2R2Control S2T2: S2WCD0 S2R2CD25 S2T3: S2WCD0N80 S2R2CD25N75
Manure applied	December each year	June each year
^a Residue return (%)	5	5
Tillage system	Conventional	Conventional
Water management	Flooded condition, water supplied mainly by irrigation for S1R1 and rainfall for S1R2.	Water supplied mainly by rainfall for S2R2 while no flooded for WS2.

R1: Irrigated rice; R2: Rainfed rice; W: wheat; FYM: farmyard manure; CD: Cowdung.

S1R1: Irrigated rice for site 1; S1R2: Rainfed rice for site 1.

S1T1: Control treatment for site 1; S1T2: Mineral N application for site 1; S1T3: Combination of mineral N and FYM for site 1.

S1R1Control: no input for S1R1; S1R2Control: No input for S1R2; S1R1N90: 90 kg N ha⁻¹ yr⁻¹ for S1R1, S1R2N90: 90 kg N ha⁻¹ yr⁻¹ for S1R2.

S1R1FYM5N90: 5 t ha⁻¹ FYM applied only once a year before R1 cropping seasons; mineral N at a rate of 45 kg N ha⁻¹ yr⁻¹ applied until 2012 after which the rate changed to 90 kg ha⁻¹ yr⁻¹.

S1R2FYM0N90: No FYM added before R2 cropping seasons; 90 kg N ha⁻¹ yr⁻¹; mineral N at a rate of 45 kg N ha⁻¹ yr⁻¹ applied until 2012 after which the rate changed to 90 kg ha⁻¹ yr⁻¹.

S2W: Wheat for site 2; S2R2: Rainfed rice for site 2.

S2T1: Control treatment for site 2; S2T2: Treatment receiving CD for site 2;

S2T3: Combination of CD and N for site 2.

S2WControl: No input for S2W; S2R2Control: No input for S2R2.

S2WCD0: No CD added before W growing seasons; S2R2CD25: 25 t ha⁻¹ fresh CD applied once a year before R2 growing seasons.

S2WCD0N80: No CD added before W growing seasons; 80 kg N ha⁻¹ yr⁻¹ for S2W.

S2R2CD25N75: 25 t ha⁻¹ fresh CD applied once a year before R2; 75 kg N ha⁻¹ yr⁻¹ for S2R2.

^a The values here as estimated.

after sowing of wheat seeds. Management and treatment of rainfed rice is almost the same as for S1. The cropping season for wheat (W) and rainfed rice for this site are identified as S2W and S2R2, respectively. The detailed description for both sites can be found in Karim et al. (1995); Egashira et al. (2003), 2005; Kader et al. (2017) and Islam (2003)

Daily weather data, including maximum temperature, minimum

temperature and rainfall for the period from 1970 to 2015 were collected from the Bangladesh Meteorological Department (BMD). Weather data from the meteorological station of Mymensingh were used for S1 which is about 400 m away from the experimental site. Weather data from Dhaka meteorological station were used for S2, which is around 40 km away from the experiment. The experimental area has a sub-tropical humid climate that is characterized by hot and humid summers and cool winters, with an annual mean temperature of 25.8 °C and rainfall of about 200 cm, 80% of which falls between May and September (BMD, 2016). The coolest months are December–January (10–15 °C) and the mean monthly hottest temperatures are in June–August (30–35 °C).

2.2. SOC and yield data

SOC and yield data for the S1 were collected every 4 to 6 years. Each SOC value was a mean of three replicate samples, but the individual values were not available. The bulk density (BD) value for this site was only measured at the time of first sample collection, and the remaining years were assumed to have the same value. Both SOC values and yield data for the S2 for 1988–1993 are available in Karim et al., (1995), and for 2003 from Egashira et al. (2003). Data from 2000 and 2008 for both SOC and yield parameters were taken from unpublished thesis papers (Hoque, 2008; Kader, 2012; Islam, 2003) in addition to our own studies. As of S1, each SOC value for S2 was a mean of three replicate samples. BD for this site was measured before the experiment and each year between 1988 and 1993 at 0–5, 5–15, 20–25 cm depth (Table 1), and after 1993 only for the 0–15 cm depth.

2.3. Model description and simulations

The DayCent biogeochemical model (Daycent-Rice version) is the daily time step version of the CENTURY model (Parton et al., 1998). DayCent simulates soil organic matter (SOM) decomposition, nitrification and denitrification, plant production and soil water dynamics. Plant production is calculated using a radiation use efficiency calculation that has both genetic and environmental components, and the potential growth is modified by impacts of soil water content, temperature, shading, CO₂ concentration and nutrient limitation (Hartmann et al., 2016). C fixed through photosynthesis is the major C input to the soil and is subdivided into two structural and metabolic litter pools. The new version of DayCent includes a methanogenesis sub-model (Cheng et al., 2013), which allows simulation of the C and N dynamics under anaerobic conditions.

To determine the initial size of SOM pools for the model simulations, average historical land use information was obtained from different sources (Kuddus and Talukder, 1981; Karim et al., 1995 and site manager's knowledge). The spin up for the first site involved grass with low intensity grazing for 1600 years followed by arable cropping with manure fertilization equivalent to 80 kg N ha⁻¹ yr⁻¹ for 300 years, until the initiation of the experiment. The second site was simulated according to known site history with a deciduous forest until 1980, and then converted into a grassland for five years before the experiment started.

2.4. Model set up to evaluate soil C and N dynamics for each plot

Most model parameters in this study were set to default values, as determined for the rice version (Cheng et al., 2013; Hartmann et al., 2016). To represent different rice cultivars for the two growing seasons, default PRDX (coefficient for potential plant production calculated using radiation use efficiency) values were set to 3.30 and 3.00 for irrigated and rainfed rice, respectively, and for wheat the PRDX was set to 1.50, the values keep fixed for all treatments for both sites. Since the model simulates soils to a depth of 20 cm, initial SOC stocks (t ha⁻¹) at 15 cm were rescaled to 20 cm by multiplying by 1.33 to scale, so that

measured and modelled values could be compared. For the second site, SOC was summed in t ha^{-1} to 20 cm depth, and it was assumed there were no differences in bulk density between 15–20 cm and the 20–25 cm depth. Since BD cannot be altered during model simulations, we used the initial BD values for the respective depth measured before the start of the experiment, although soil BD is known to have changed by approximately 20% in the CD containing plot at S2 in 2008 compared to values at the start of the experiment (Hoque, 2008). Previous long term analysis on SOC stock calculations were done by adjusting standard soil weight (Smith et al., 1997; Begum et al., 2017), or by adjusting model outputs due to changing BD (Smith et al., 1997). Without adjusting modelled SOC stock, DayCent (DailyDayCent) was applied in the plot receiving manure from the period of 1843 onwards on the well-documented long term Rothamsted Broadbalk monoculture wheat site, and a highly significant positive relationship between modelled and measured SOC was found ($r = 0.87$), without significant bias (Begum et al., 2017). In the current study simulations with fixed BD in the manured plot also showed a highly significant correlation between model and measurement (Table 4, S1T3 and S2T2). Furthermore, an additional model experiment (results not shown) which varied BD by 20% at this site, showed that relative changes of SOC were very small at around 3%. This shows that changing BD will not have greatly changed our findings, confirming earlier finding with the same model (Begum et al., 2017). The model is adequate based on the statistics that was estimated, and can therefore be used to predict SOC changes and emission reductions under various combinations of management practices – which is the subject of interest in this study.

To simulate the impact of additional sources of organic matter, for example from algae and aquatic weeds, which can contribute about $0.5\text{--}2\text{ t C ha}^{-1}\text{ yr}^{-1}$ to paddy soils (Bronson et al., 1997; Pampolino et al., 2008; Roger and Ladha, 1992), we add this quantity of carbon as an organic amendment, adding $750\text{ kg C ha}^{-1}\text{ crop}^{-1}$ with a C/N ratio of 12 (Bronson et al., 1997), and applying it just before drainage, assuming that the carbon input occurs when the land is drained. An annual additional N source of $60\text{ kg N ha}^{-1}\text{ yr}^{-1}$ was also considered for double rice cropping systems, assuming $20\text{ kg N ha}^{-1}\text{ yr}^{-1}$ from wet and dry deposition, and $20\text{ kg N ha}^{-1}\text{ crop}^{-1}$ as microbial N fixation, based on values in the literature (Mian et al., 1991; Pampolino et al., 2008; Roger and Ladha, 1992). For the second site, 500 kg C was used as the representative additional input. As a non-rice crop was grown in the first growing season at S2, $20\text{ kg mineral N ha}^{-1}\text{ yr}^{-1}$ was added in the second (rice growing) season to mimic microbial N fixation during that season (as at S1).

2.5. Statistical methods

Performance of the DayCent model was tested using the statistical model evaluation routines provided in MODEVAL (Smith et al., 1997; Smith and Smith, 2007). The sample correlation coefficient (r) was used (Eq. (1)) to test for association between the modelled and measured values over time. The mean difference (M) between observation and simulation was calculated to assess bias in the modelled results (Eq. (2)). Modelled and measured SOC and yield were also compared by calculating the root mean square error (RMSE, Eq. (3)), which indicates total difference between observed and predicted values (Smith et al., 1997).

$$r = \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \quad (1)$$

$$M = \frac{\sum_{i=1}^n (O_i - P_i)}{n} \quad (2)$$

$$RMSE = \frac{100}{\bar{O}} \sqrt{\sum_{i=1}^n (P_i - O_i)^2 / n} \quad (3)$$

where $\bar{O}$ and $\bar{P}$ are the mean values of observed and predicted data,

respectively, and O_i and P_i indicate the observed and predicted values of the i th iteration, respectively, and n is the number of samples. The significance of r and M were tested using a Student's two-tailed t -test (critical at 2.5%), and F-test (at probability levels of $p = 0.05$, 0.01 and 0.001), respectively. The simulated and measured yield under different nutrient treatments were evaluated using linear regressions and associated R^2 values.

2.6. Baseline simulations and mitigation scenarios

The baseline fertilizer management consisted of a single N application at the current rate of $180\text{ kg N ha}^{-1}\text{ yr}^{-1}$ for S1 (S1T2 Table 1), while for S2, the CD application ($25\text{ t ha}^{-1}\text{ yr}^{-1}$) was selected (S2T2 Table 1). These practices match current agricultural management in these two areas of Bangladesh. Along with fertilizer, the baseline management for both sites included 5% residue return (Rsd5), conventional tillage (CT) and continuous flooding. We evaluated 4 mitigation scenarios for each site, including reduced tillage (RT), residue management, and modifications of fertilizer and manure application (manure was assumed to be FYM at S1 and CD at S2, to match current practice). One integrated scenario was tested for each site. Since S1R1 is flooded with irrigation water for the entire cropping season, we evaluated alternate wetting and drying (AWD) cycles as a mitigation practice alone, and with the integrated management options described above. Therefore, a total of seven scenarios were considered for S1, and five scenarios were considered for S2. Management in the baseline was constant, while for the alternative scenarios, one management practice was modified relative to the baseline conditions, and for the integrated management scenario, a number of practices were varied. Details of baseline and mitigation scenarios are summarized in Table 2.

2.7. Annualized SOC stocks and GHG emissions

For quantification of the mitigation potential, annualized C stock changes were calculated as the difference between the final SOC stock for the mitigation scenario and the final SOC for the baseline scenario, divided by the number of years in the projection. The period 1988–2015 was selected for S1 and 1988–2008 for S2, based on the time periods of the experiments.

CH_4 and N_2O data were not available in the observations to calibrate DayCent at either of the test sites, so we estimated CH_4 (Lasco et al., 2006) and N_2O (De Klein et al., 2006) emissions using default emission factors (EFs) of the Intergovernmental Panel on Climate Change (IPCC) tier 1 methods for the three potential integrated mitigation scenarios (two scenarios from site 1 and one from site 2). We determined net GHG balances ($(\text{CH}_4 + \text{N}_2\text{O}) + (-\text{SOC})$) using global warming potentials (GWP) ($\text{CO}_2\text{-eq.}$) over a 100 year time span (Forster et al., 2007). For estimation of CH_4 from these three integrated management options, we used IPCC values which provide EFs and scaling factors for water regimes and organic amendment. Khan and Saleh (2015) estimated CH_4 emissions from rice fields (irrigated and rainfed rice) in Bangladesh for the period of 2000–2009 following IPCC guidelines. Following their methodology we have used the default IPCC baseline EF ($1.3\text{ kg CH}_4\text{ ha}^{-1}\text{ day}^{-1}$) and the default scaling factor for water regimes, while the scaling factor for rice residue and organic amendment were modified, based on the information available (Khan and Saleh, 2015). The country specific seasonal EF for CH_4 was estimated by FAOSTAT (2017) as 9.94 g m^{-2} ; assuming 120 days, the EF would be approximately $0.83\text{ kg CH}_4\text{ ha}^{-1}\text{ day}^{-1}$ which was also used in this study to calculate CH_4 emissions from Bangladesh paddy field. For determining N_2O emissions from paddy rice, the IPCC default EF of 0.003 (0.3% of applied fertilizer) was used, along with a higher EF for AWD systems (0.6% of applied fertilizer; Shepherd et al., 2015), as found in Chinese paddy fields. Studying two rice test sites in Bangladesh, Gaihe et al., (2015) found different EF for irrigated and rainfed rice under continuously flooded conditions of 0.003 and 0.0004

Table 2

Baseline (180 kg N ha⁻¹ yr⁻¹ for site 1, and 25 t ha⁻¹ yr⁻¹ cowdung for site 2, respectively) and different mitigation scenarios, on Bangladesh two long-term, rice-based test sites.

Management activity	^a Scenarios for site 1	Abbreviation for site 1	^a Scenarios for site 2	Abbreviation for site 2
Baseline (current farmers' Practice)	180 kg N ha ⁻¹ yr ⁻¹ (N180), 5% residue return (Rsd5) and CT	BLS1_N180	25 t ha ⁻¹ CD application (contained 83 kg mineral N), Rsd5 and CT	BLS2_CD25
Residue return 20% (Rsd20)	Rsd20	SCN_1A_Rsd20	Rsd20	SCN_1B_Rsd20
Reduced tillage (RT)	Sowing with less disturbance to the topsoil in place of traditional ploughing	SCN_2A_RT	Sowing with less disturbance to the topsoil in place of traditional ploughing	SCN_2B_RT
N application	20% less N than BLS1_N180	SCN_3A_N144	Substitution of manure with mineral N fertilizer (83 kg N ha ⁻¹ yr ⁻¹)	SCN_3B_N83
Manure application (FYM or CD)	Substitution of baseline mineral N by FYM	SCN_4A_FYM8	50% more CD than applied as baseline (BLS2_CD25)	4B_CD38
Water management (AWD)	Apply water with controlled irrigation under R1 cropping season	SCN_5A_AWD	NA	
Integrated management (IM)	15% less N than BLS1_N180, 15% less residue, Rsd15, RT and FYM5	SCN_6A_N153 + Rsd15 + RT + FYM5 (SCN_6A_IM1)	153 kg N ha ⁻¹ Rsd20, RT and baseline CD (BLS2_CD25)	SCN_5B_N153 + Rsd15 + RT + CD25 (SCN_5B_IM)
	15% less N than BLS1_N180, 15% less residue (Rsd15), RT, FYM5 and AWD	SCN_7A_N153 + Rsd15 + RT + FYM5 + AWD (SCN_7A_IM2)		

FYM: farmyard manure, CD: cowdung.

NA: Not practised in this site.

^a The mitigation management in column 2 and 4 indicates only the modified option, other management were as same as in baseline.

respectively. As no data was available for AWD in their research, we obtained N₂O emissions data under AWD from Ali et al., (2013). Assuming N₂O emissions under non-amended soil of 0.067 kg ha⁻¹ (Gaihre et al., 2015) we calculated the EF under AWD systems to be 0.005. The N₂O EF for wheat was assumed to be 0.01 (1% of applied fertilizer as suggested by the IPCC. Therefore, overall GHG balances were compared using IPCC estimated default EFs and scaling factors, and country-specific EFs obtained from published sources.

3. Results

3.1. Modelled and measured yield

A highly significant positive correlation ($p < 0.001$) was observed between modelled and measured yield in S1 and S2 for all treatments together (Fig. 1). A good association with limited bias (underestimated by 0.25 t ha⁻¹ yr⁻¹) was also observed for yield in the rice and wheat growing seasons under different management practices when examining both sites together (Table 2). However, association was found

to be non-significant between modelled and measured yield if assessed for individual cropping seasons. Yield was underestimated (about 1.20 t ha⁻¹ yr⁻¹) by the model in the control plot of irrigated rice in S1 (S1R1Control) and for rainfed rice at S2 (S2R2Control), while it was overestimated for wheat in the control (S2WControl) and CD plots (S2WCD0). Except the control treatment the RMSE between model and measurement for both sites was < 40% (Table 3).

3.2. Modelled and measured SOC

Both modelled and observed results for S1 and S2 revealed that SOC increased over time (Fig. 2) under all treatments. The observed SOC changes over a 37 year time period for S1 was around 14, 11 and 15 t ha⁻¹ from S1T1, S1T2 and S1T3, respectively, while values simulated by DayCent under theses management practices were 10, 14 and 17 t ha⁻¹ respectively. For S2, observed SOC changes were 11, 9 and 14 t ha⁻¹ for S2T1, S2T2 and S2T3 over a 20 year time period, where the model simulated values of 3, 12 and 13 t ha⁻¹, respectively. There is a significant positive relationship between modelled and measured SOC

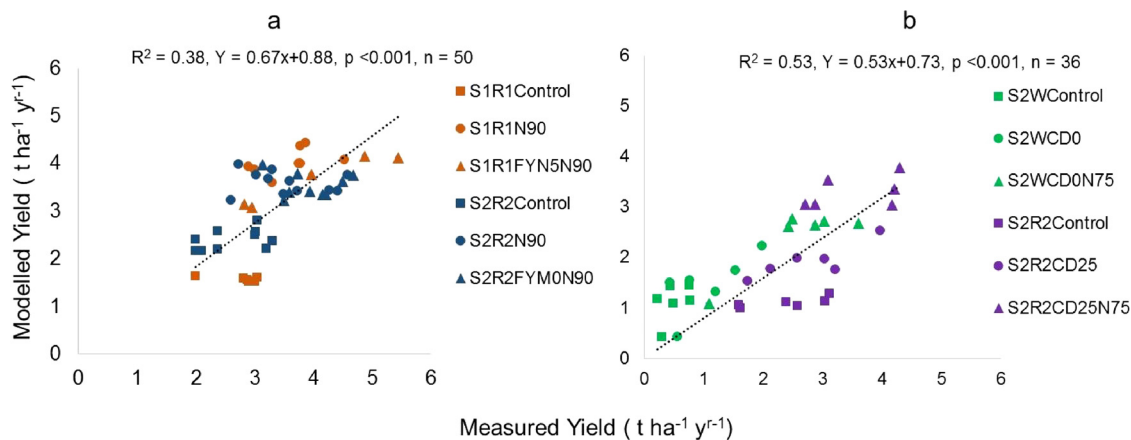


Fig. 1. Modelled and observed yield under three different treatments for both cropping seasons of two long term test site 1 (a) and site 2 (b) (dotted line indicates 1:1). Each dot represents yield (rice or wheat) of one cropping season. There are 5–11 values per treatment (please see Table 3) which results in an overall sample size of $n = 86$.

Table 3

The calculation of r , M and $RMSE$ showing F ($P = 0.05, 0.01, 0.001$) and critical t (2.5% Two-tailed) between simulated and observed yield at the two long term rice based test sites Bangladesh under different treatments.

Sites	Treatment	r	M (t ha ⁻¹ yr ⁻¹)	$RMSE$ (%)
Site 1	S1R1Control (6)	-0.68 ^{ns}	1.20 ⁺	45.34
	S1R2Control (11)	0.37 ^{ns}	0.30 ^{ns}	20.85
	S1R1N90 (n = 8)	0.50 ^{ns}	-0.41 ^{ns}	16.43
	S1R2N90 (n = 11)	0.10 ^{ns}	0.08 ^{ns}	17.38
	S1R1FYM5N90 (n = 5)	0.96 ^{**}	0.36 ^{ns}	17.32
	S1R2FYM0N90 (n = 9)	-0.11 ^{ns}	0.40 ^{ns}	17.24
	All treatments (n = 50)	0.62 ^{***}	-0.24 ⁺	21.99
	S2WControl (6)	0.46 ^{ns}	-0.62 ⁺	140.11
	S2R2Control (6)	0.85 ^{ns}	1.28 ⁺	58.38
	S2WCD0 (n = 6)	0.76 ^{ns}	-0.86 ⁺	35.59
Site 2	S2R2CD25 (n = 6)	0.92 ^{***}	0.72 ⁺	36.24
	S2WCD0N80 (n = 6)	0.86 ^{ns}	0.16 ^{ns}	16.62
	S2R2CD25N75 (n = 6)	0.43 ^{ns}	0.25 ^{ns}	18.50
	All treatments (n = 36)	0.74 ^{***}	0.26 ^{ns}	39.53
	S2WControl (6)	0.46 ^{ns}	-0.62 ⁺	140.11
	S2R2Control (6)	0.85 ^{ns}	1.28 ⁺	58.38
	S2WCD0 (n = 6)	0.76 ^{ns}	-0.86 ⁺	35.59
	S2R2CD25 (n = 6)	0.92 ^{***}	0.72 ⁺	36.24
	S2WCD0N80 (n = 6)	0.86 ^{ns}	0.16 ^{ns}	16.62
	S2R2CD25N75 (n = 6)	0.43 ^{ns}	0.25 ^{ns}	18.50
Site 1 and site 2	All treatments (n = 86)	0.77 ^{***} ($R^2 = 0.60$, $p < 0.001$)	0.25 ⁺	27.53

n = number of samples.

R1: Irrigated rice; R2: Rainfed rice; W: wheat; FYM: farmyard manure; CD: Cowdung.

S1R1: Irrigated rice for site 1; S1R2: Rainfed rice for site 1.

S1R1Control: no input for S1R1; S1R2Control: No input for S1R2; S1R1N90: 90 kg N ha⁻¹ yr⁻¹ for S1R1, S1R2N90: 90 kg N ha⁻¹ yr⁻¹ for S1R2.

S1R1FYM5N90: 5 t ha⁻¹ FYM applied only once a year before R1 cropping seasons; mineral N at a rate of 45 kg N ha⁻¹ yr⁻¹ applied until 2012 after which the rate changed to 90 kg ha⁻¹ yr⁻¹.

S1R2FYM0N90: No FYM added before R2 cropping seasons; 90 kg N ha⁻¹ yr⁻¹; mineral N at a rate of 45 kg N ha⁻¹ yr⁻¹ applied until 2012 after which the rate changed to 90 kg ha⁻¹ yr⁻¹.

S2W: Wheat for site 2; S2R2: Rainfed rice for site 2.

S2T1: Control treatment for site 2; S2T2: Treatment receiving CD for site 2; S2T3: Combination of CD and N for site 2.

S2WControl: No input for S2W; S2R2Control: No input for S2R2.

S2WCD0: No CD added before W growing seasons; S2R2CD25: 25 t ha⁻¹ fresh CD applied once a year before R2 growing seasons.

S2WCD0N80: No CD added before W growing seasons; 80 kg N ha⁻¹ yr⁻¹ for S2W.

S2R2CD25N75: 25 t ha⁻¹ fresh CD applied once a year before R2; 75 kg N ha⁻¹ yr⁻¹ for S2R2.

* Significant correlation (r) between modelled and measured SOC at $p < 0.05$, or significance mean error (M) at $p = 0.025$.

** Significant correlation (r) between modelled and measured SOC at $p < 0.01$.

^{ns} = non-significant.

and a good agreement ($RMSE < 20\%$) between observed and simulated SOC trends at S1 under different nutrient management practices including the control treatment (Fig. 2a and Table 4). A good association ($RMSE < 20\%$) was also observed at S2 under the treatment associated with CD (S2T2) and CDN (S2T3), while the $RMSE$ value was slightly higher (23%) and a non-significant positive relationship was attained under the control plot (S2T1, Fig. 2b and Table 4). No significant bias was found in any simulation.

3.3. Modelled yield and SOC under different mitigation scenarios

Simulated yield for irrigated rice at S1 and rainfed rice at S2 are shown for growing season S1R1 and S2R2, respectively (Fig. 3a and c). Modelled results showed that, among the selected mitigation scenarios,

Table 4

The calculation of r , M and $RMSE$ showing F ($P = 0.05, 0.01, 0.001$) and critical t (2.5% Two-tailed) between simulated and observed SOC at the two long term Bangladesh rice based test sites under different treatments.

sites	Treatment	r	M (t ha ⁻¹ yr ⁻¹)	$RMSE$ (%)
Site 1	S1T1 (n = 8)	0.83 ^{**}	0.79 ^{ns}	18.89
	S1T2 (n = 8)	0.75 ⁺	-1.19 ^{ns}	17.90
	S1T3 (n = 8)	0.90 ^{***}	0.56 ^{ns}	8.78
Site 2	S2T1 (n = 9)	0.51 ^{ns}	2.11 ^{ns}	23.41
	S2T2 (n = 9)	0.91 ^{***}	-1.39 ^{ns}	13.66
	S2T3 (n = 4)	0.93 ^{ns}	-0.93 ^{ns}	10.69

n = number of samples.

S1T1: Control treatment for site 1; S1T2: Mineral N application for site 1; S1T3: Combination of mineral N and farmyard manure FYM for site 1.

S2T1: Control treatment for site 2; S2T2: Treatment receiving cowdung for site 2; S2T3: Combination of cowdung and mineral N for site 2.

* Significant correlation (r) between modelled and measured SOC at $p < 0.05$, or significance mean error (M) at $p = 0.025$.

** Significant correlation (r) between modelled and measured SOC at $p < 0.01$.

*** Significant correlation (r) between modelled and measured SOC at $p < 0.001$.

^{ns} = non-significant.

the average yield was stable over 20 years (varying from 3.5–3.6 t ha⁻¹ yr⁻¹), except for the scenario using only FYM instead of mineral fertilizer (SCN_4A_FYM8), where yield was reduced by 18%. No yield penalty was obtained if reducing mineral fertilizer by 20% of its current rate as our modelled results showed (SCN_3A_N144). The maximum yield at S2 was observed when an integrated approach was used (SCN_5B_IM); around 3.34 t ha⁻¹ yield was attained which is about 50% higher than yield under current conditions. The scenario with a greater CD application rate (SCN_4B_CD38) increased yield by 20%, while a slight yield decline was observed (about 7%) by modification of current tillage management (SCN_2B_RT) at this site.

The simulation results for SOC (Fig. 3b and d), under the different scenarios compared to baseline conditions, demonstrate that all management options at S1 increase SOC in comparison to the baseline, except two scenarios. No impact on SOC changes was observed under the model simulations with reduced mineral N application (SCN_1A_N144), while slight decrease (3%) in SOC was found when water management changed from continuous flooding to AWD (SCN_4A_AWD). Among the scenarios applying single measures, the application of FYM tends to increase SOC by 60%, the maximum SOC increase for S1. Integrated management, with (SCN_7A_IM2) and without AWD (SCN_6A_IM1), increased SOC up to 23%. Compared to the baseline, changes in tillage or residue management tended to increase SOC by up to 7% at S1. Lower SOC (20%) was seen at S2 for model simulations with application of mineral N instead of manure (SCN_3B_N83). Increases in SOC of 4–30% can be achieved with other mitigation scenarios, with the maximum occurring under integrated management.

Model-based SOC change from both sites over 20 years suggests that changes in tillage and residue management can lead to an increase in SOC of 0.06–0.27 t C ha⁻¹ yr⁻¹ (Table 5). Due to low C input, the use of N application instead of manure does not increase SOC stock at S1, and leads to SOC loss at S2. There is a neutral or a slightly negative impact on SOC stocks with AWD water management at S1. The use of manure instead of mineral fertilizer increased SOC by 0.89 t C ha⁻¹ yr⁻¹ at S1. Integrated management is able to increase SOC stocks from the two sites by around 0.30–0.43 t C ha⁻¹ yr⁻¹. The SOC sequestration rate for S1 over a 27 year time period was estimated to be between -0.05 and 0.38 t C ha⁻¹ yr⁻¹ across different treatments.

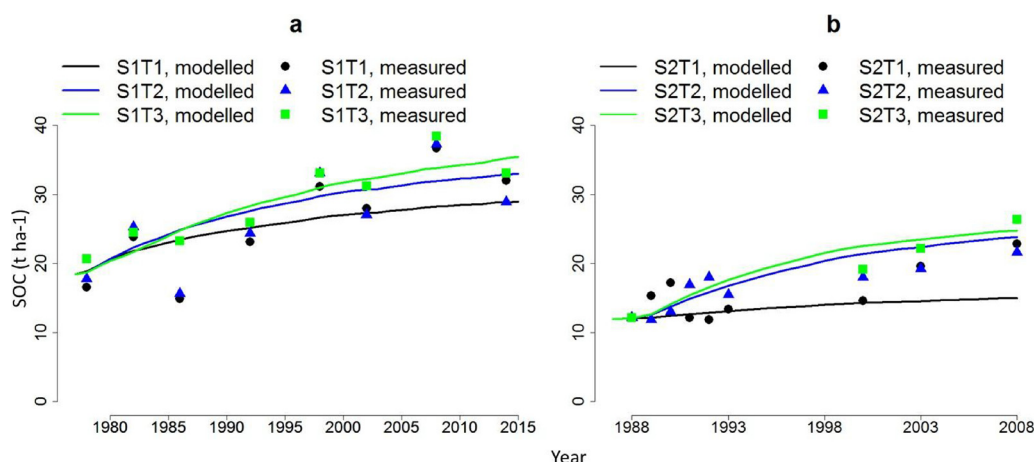


Fig. 2. Simulated (line) and measured (points) SOC values for the different treatments during the period 1978–2015 at site 1 double rice based cropland (a) and 1988–2008 at site 2 rice-wheat cropland (b) respectively in Bangladesh.

S1T1: Control treatment for site 1; S1T2: Mineral N application for site 1; S1T3: Combination of mineral N and farmyard manure (FYM) for site 1. S2T1: Control treatment for site 2; S2T2: Treatment receiving cowdung (CD) for site 2; S2T3: Combination of CD and mineral N for site 2.

3.4. Total GHG emissions

Since the climate change benefits of soil carbon sequestration can be offset or even negated by emissions of non-CO₂ GHGs (N₂O and CH₄), it is important to assess the likely impact of any change in management practice on the total GHG balance. Using IPCC default EFs to assess the net GHG balance (CO₂-eq. ha⁻¹ yr⁻¹) for three potential integrated mitigation scenarios at both sites, it is revealed that under the integrated scenario at S1, which does not consider AWD (SCN_6A_IM1), CH₄ emissions increased by around 2.6 t CO₂-eq. ha⁻¹ yr⁻¹ and N₂O emissions decreased by around 0.01 t CO₂-eq. ha⁻¹ yr⁻¹, giving an overall increase in net GHG emissions 1.27 t CO₂-eq. ha⁻¹ yr⁻¹ (equivalent to 0.34 t Ceq. ha⁻¹ yr⁻¹), since additional CH₄ emissions outweigh the SOC gain (Fig. 4). For the alternative integrated

management approach, where water management was changed from CF conditions to AWD at S1 (SCN_7A_IM2), no change was found for N₂O emissions but CH₄ emissions were decreased by 0.10 t CO₂ eq. ha⁻¹ yr⁻¹, giving an overall net GHG emission reduction of 1.21 t CO₂-eq. ha⁻¹ yr⁻¹ (equivalent to 0.33 t Ceq. ha⁻¹ yr⁻¹), which indicates that this scenario could be an effective mitigation scenario for double rice cropping systems in Bangladesh. The integrated management approach on the wheat-rice cropping system at S2 (SCN_5B_IM) increased N₂O emissions (0.46 t CO₂-eq. ha⁻¹ yr⁻¹) but led to an overall reduction in net emissions compared to the baseline, by about 0.82 t CO₂-eq. ha⁻¹ yr⁻¹ (equivalent to 0.22 t Ceq. ha⁻¹ yr⁻¹). The CH₄ emissions under the selected scenario for double rice cropping systems were found to be of 238–346 kg ha⁻¹ yr⁻¹. The figure is about two times more than the value in the FAOSTAT database which is

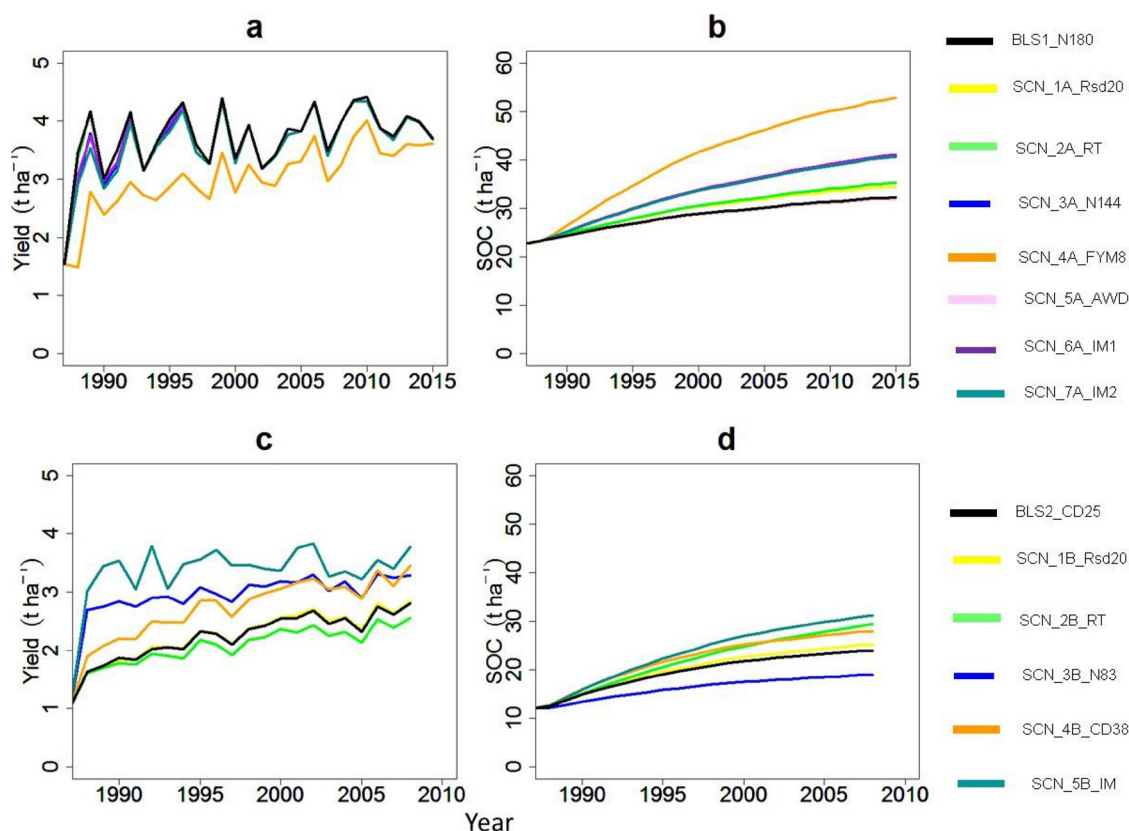


Fig. 3. Modelled yield (a, c) and SOC (b, d) under different mitigation scenarios for two long term rice based test sites Bangladesh (yield here shown for S1R1 and S2R2 cropping season). Each scenario denoted in brief in right side, details available in Table 2. Note that SCN_3A_N144 and SCN_5A_AWD overlaps with the baseline scenario, also SCN_6A_IM1 and SCN_7A_IM2 overlaps each other, so is not visible.

Table 5

Model-based, annualized, soil carbon stock change ($\text{t C ha}^{-1} \text{ yr}^{-1}$) under different management regimes relative to the baseline for two rice based test sites Bangladesh over 20 and 27 year periods.

Management activity	Site 1 (1988–2008)	Site 2 (1988–2008)	Site 1 (1988–2015)
Rsd20	0.10	0.06	0.08
RT	0.12	0.27	0.11
AWD	−0.05	NA	−0.05
^a N application	0.001	−0.25	0.00
^b Manure addition	0.89	0.20	0.75
^c IM	0.30–0.36	0.36	0.26–0.33

Rsd20: Residue return 20%; RT: Reduced tillage.

^a Less mineral N than baseline for site 1 and /replacement of manure instead of mineral N for site 2 respectively.

^b N substitution for site 1 and more manure application than the baseline for site 2 respectively. Manure indicated farmyard manure (FYM) for site 1 and cowdung (CD) for site 2 respectively. Details description of each scenario are available in Table 2.

^c Integrated management, SCN_6A_IM1 and 7A_IM2 for site 1 for the period 1988–2008 and 1988–2015, SCN_5B_IM for site 2 for the period 1988–2008.

computed based on Tier 1 IPCC 2006 Guidelines for National GHG inventories (FAOSTAT, 2017). The N_2O emissions calculated here was based on the IPCC default EF of 0.003, but for the AWD scenario (SCN_7A_IM2), N_2O emissions were 9 times higher when calculated using an EF estimated by previous studies for Bangladesh rice soil (Ali et al., 2013; Gaihr et al., 2015) (data not shown). In contrast to a reduction of net GHG balance of $1.21 \text{ t CO}_2\text{-eq. ha}^{-1} \text{ yr}^{-1}$ under the SCN_7A_IM2, a value of around $1.11 \text{ t CO}_2\text{-eq. ha}^{-1} \text{ yr}^{-1}$ was found using a country-specific EF for N_2O emissions (data not shown).

4. Discussion

4.1. Modelled yield and SOC

Among the three treatments, the lowest yields were observed under the no nutrient input treatments, though average rice production for both sites under the control treatment was around $2\text{--}3 \text{ t ha}^{-1} \text{ yr}^{-1}$. It appears that there are other N sources supporting plant growth other than the inputs through fertilization and atmospheric deposition, and mineralization of residues and SOM. This N could be supplied by blue green algae (BGA) or other aquatic biomass (azolla, weeds) that grow in the standing water with the main crop and during the fallow period. The contribution of microbial N fixation on the paddy fields was not

measured, but was estimated to be $30\text{--}40 \text{ kg ha}^{-1} \text{ yr}^{-1}$ at S1 (Mian et al., 1991). In a meta-analysis of 114 long term studies (1961–2010) across 21 countries on fertilized paddy rice, Ladha et al. (2016) estimated that nearly $38 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (48% of the amount of N taken up by plants) was from sources other than fertilizer. They found that about half (about $20 \text{ kg ha}^{-1} \text{ yr}^{-1}$) was contributed by non-symbiotic biological N fixation. After 15 years of intensive rice cultivation, Pampolino et al., (2008) found from 19 to $44 \text{ kg N ha}^{-1} \text{ crop}^{-1}$ of additional N input in a double rice cropping with all crop residue incorporated, and triple rice cropping with crop residue removed, and reported that the figure would be larger if leaching or runoff losses were considered. Roger and Ladha (1992) reviewed the contribution of N sources in wet land rice soils separately from different sources including photo-synthetic bacteria, BGA, and azolla using different methodologies, and found N balances in long term unfertilized plots of $19\text{--}98 \text{ kg N ha}^{-1} \text{ crop}^{-1}$, with an average of $50 \text{ kg N ha}^{-1} \text{ crop}^{-1}$, and for rice with upland crops of $44 \text{ kg N ha}^{-1} \text{ yr}^{-1}$. N supplied by urea has a negative impact on the algal population on flooded soils (Simpson et al., 1994). All of these findings suggest that external sources of C and N need to be considered when estimating the C and N balance of paddy rice ecosystems. By examining a large set of Bangladeshi paddy soils (Kader et al., 2013) and for these sites (Kader et al., 2017), it was concluded that anaerobic N mineralization in paddy soil is not as straightforward as for aerobic soils, and is not solely dependent on SOM quantity. It has been hypothesized that the presence of alternative electron acceptors (ferric and sulphate ion), soil enzymes, and phenolic compounds of SOM influence the N mineralization in paddy soil under anaerobic conditions (Kader et al., 2017).

In preliminary simulations, N and C inputs from aquatic biomass, were not included, and yield simulations under double rice cropping systems were poor ($RMSE > 75\%$ and systematic bias, outputs not shown). The additional C and N input greatly improved the performance of the model on the unfertilized plots. Since DayCent is not able to grow two crops/plants together and cannot simulate natural aquatic plants growth in the water along with main crop rice, it was assumed that the C and N inputs would be accumulated in the aquatic biomass and incorporated into the soil upon drainage. The simulations presented in this manuscript therefore consider the additional input of N and C using realistic values from the literature, which also reduced the discrepancy between modelled and measured values in the preliminary runs when the external sources were not considered. Nevertheless, the inclusion of additional N and C sources did not fully close the gap between simulated and observed values in the unfertilized plots at the two sites. At S2, including mineral N fertilizer to mimic microbial N fixation during the rice growing seasons tended to impact on the following crop



Fig. 4. Greenhouse gas emissions and net GHG balance estimated with IPCC guidelines (for N_2O and CH_4 using GWP over 100 year time span) under selected mitigation scenarios at two rice test sites in Bangladesh. Negative values denote a removal of GHG from the atmosphere and positive values denote increased emissions to the atmosphere. See Table 4.2 for a detailed description of the scenarios.

of wheat, by adding C and N from crop residue input of the previous, which could lead to an over prediction of wheat growth. Considering additional C and N input is important when simulating rice-based double cropping systems. In this study, there were only 5 to 11 yield measurements for each treatment, and taking all of the yield data together, for both cropping seasons under all treatments, we find overall a good prediction of yield by DayCent ($R^2 = 0.60$; $p < 0.001$). A highly significant relationship was also found using DayCent to simulate yield in Chinese croplands (350 sites) including rice grown continuously or in rotation with other crops ($R^2 = 0.81$, $p < 0.001$) (Cheng et al., 2014).

Regarding SOC simulations on the control plots, our preliminary model test (not shown) predicted a loss of SOC over time, even though the soil was under anaerobic conditions for long period, and this trend did not match with the measurements (not presented). Considering exogenous sources in the simulations presented here, an average annual input of C of about $1.2 \text{ t ha}^{-1} \text{ yr}^{-1}$ was found in the control simulations, which matched well with the observations trend. Our findings are consistent with those of Pampolino et al., (2008), who reported that, regardless of fertilizer or residue incorporation, root residues and exogenous organic amendment, e.g. algae, azolla in the soil flood water, would contribute to C and N balance. They also found no significant difference on SOC changes with fertilizer and without fertilizer N in an irrigated low land rice soil over a 15 year time period. In the field study, the increase of SOC in the control plot and the plot receiving mineral N each year was nearly similar (or higher) to that of the N fertilized plot. By analyzing SOC data for 2008 under different treatments on the two test sites, Kader et al., (2017) found no statistically significant difference in SOC content between unfertilized control and N fertilized paddy soils. SOC was found to be increase by 25–40% in the plot receiving mineral fertilizer than the control plot at long term rice based cropland in India (Bronson et al., 1997). Applying mineral N fertilizer in the MN plot tends to stimulate yield growth in DayCent which also delivers more residue to the soil, thereby increasing SOC, on average by 25% than SOC simulated under control plot. Apart from the treatment S2T3 that showed the output associated with only 4 measurements, a good agreement between modelled and measured SOC was observed in the tested sites with no bias. A good agreement between modelled and measured SOC under irrigated ($R^2 = 0.71$) and rainfed rice ($R^2 = 0.74$) was found in China using the DayCent model, but modelled SOC was significantly underestimated by 28% and 48%, respectively (Cheng et al., 2014).

4.2. Yield and SOC changes under mitigation scenarios

The main purpose of the current study was to estimate emission reductions under various combinations of management practices. Although our model results revealed that current management contributes to an increase in SOC over the study period, our aim was to examine practices that improve soil quality and soil health, and store additional SOC without compromising yield. Most of the selected scenarios tend to increase SOC and maintain a stable yield when compared to the baseline, but the scenario giving the maximum yield was not the same as that giving maximum SOC increase (Fig. 3). For Bangladesh, it is critical that mitigation options do not compromise yield. Therefore, we concentrate in the discussion on the mitigation scenarios with a neutral or positive effect on yield. For instance the greatest SOC increase was predicted to occur for the scenarios with increased single manure (FYM or CD) application, but under these scenarios, the yield declined. By observing yield trends in 25 long term experiments (at least 10 years) with double rice and rice-wheat cropping systems in Asia, Dawe et al., (2003) did not find positive impact under FYM or straw application and stated that organic material could not be the major nutrient source. In addition, there is a limited supply of cowdung, since it has many alternative uses in Bangladesh. It is estimated that, annually, around 125 Mt fresh cowdung is produced in Bangladesh from 23 million cattle, of which around 56% is managed in solid

storage and the rest is used for fuel, a feedstock for anaerobic digesters or other purposes (BLRI, 2017). Our model results show that it is possible to reduce fertilizer quantities by 30% compared to current application rates without yield penalty, if additional sources of C and N are accounted for. Currently, only about 1 Mt of urea is produced in Bangladesh (FAOSTAT, 2017), while the requirement to apply mineral N to the entire cropland area at the recommended dose is estimated to be three times greater (FRG, 2012; FAOSTAT, 2017).

Modification of tillage can increase SOC and can compensate for the additional manure (CD) application at S2, as both options show almost the same SOC increase at the end of the year. RT is likely to increase SOC content by reducing decomposition. RT/no tillage (NT) causes less disturbance in the top soil layer, and is not as deep as CT, which is beneficial for several physical and biological soil properties (Chen et al., 2017; Ogle et al., 2012), including increased physical protection of soil organic matter through improvement of soil aggregation (mainly micro-aggregation) (Kader, 2012; Kader et al., 2010; Six et al., 2000). Practising RT, or promoting residue accumulation, as a single management approach has been suggested as a mechanism to sequester C in Chinese rice paddies; however, on modification of only tillage management, there might be a risk of weed accumulation or incidence of disease, due to less inversion of soil in RT management. Further, the risk of N_2O and CH_4 emissions could increase with more residue accumulation (Freibauer et al., 2004). It is important, therefore, to consider both residue accumulation with NT or RT, and increased SOC sequestration by increased C inputs (Yan et al., 2007), all of which were found to be important by Ghimire et al., (2017) in South Asian, rice-based cropping systems. Farmers in developing countries like Bangladesh might not be convinced to retain residues on the field, since alternative uses including fodder for cattle, and fuel are considered profitable (Hossain, 2001; Haider, 2013). RT and the incorporation of a larger proportion of crop residues can increase SOC without reducing yield. A recent study by Kader et al. (2016) (3 year field experiment on a floodplain soil) showed that increased residue retention (20%) along with adoption of RT in N fertilized soil positively influenced system yields with an increased gross return of 6%, and gross margin of 11–13% compared to the conventional low residue retention treatment in a yearly rice-wheat-mungbean cropping rotation. In another study with N fertilized test sites, the yield response with RT management on two field experiments - rice with legume crops and rice with wheat - Haque et al. (2016) observed the same yield under CT with puddling and RT without puddling. This modification of tillage also decreased GHG emissions relative to conventional puddling and transplanting (Alam et al., 2016). Lower yields occurred on the CD treated site (SCN2B_RT) due to lower N delivered to the soil and reduced decomposition, which resulted in lower N uptake by the plant.

Smith et al. (2008) estimated SOC changes for tillage and residue management in a warm-moist cropland of -0.11 – $0.49 \text{ t C ha}^{-1} \text{ yr}^{-1}$. We calculated SOC changes under tillage and residue management for rice-rice and wheat-rice crops at 0.06 – $0.27 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Table 4), which also agrees well with the above values and from other studies (Lal, 2004; Nayak et al., 2015). Our modelled values of SOC change with high nutrient input of 0.30 – $0.89 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (the scenario with only manure, manure along with mineral N and integrated management for both sites) is slightly higher than the Smith et al. (2008) estimates for nutrient and agronomic management (0.003 – $0.35 \text{ t C ha}^{-1} \text{ yr}^{-1}$), but comparable with estimated SOC sequestration potentials of 0.21 – $0.50 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in Indian paddy rice (Nayak et al., 2012; Bhattacharyya et al., 2012). Compared to the 44% increase of SOC stock over a 20 year period suggested by IPCC for improved nutrient management (manure addition) on tropical moist cropland (Smith et al., 2007), our model results with high nutrient input at both sites showed an increase of 20–60%. In studies of paddy rice in China, SOC increases as high as 76% have been suggested for treatments with manure amendments over a 40 year period (Rui and Zhang, 2010).

In our analysis, the integrated scenario was considered the best

NAMA for both sites. The mean annualised carbon stock changes relative to the baseline under the selected management scenario over a 20 year time span, is estimated to be $0.33 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for site 1, and $0.30 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for site 2, respectively. To give some context to these per-area sequestration rates, if they were applied to the entire AEZ for respective sites, the SOC stock would be estimated to increase by $0.24 \text{ Tg C yr}^{-1}$ and $0.13 \text{ Tg C yr}^{-1}$, assuming rates at sites 1 and 2, respectively. Implementing the scenario with integrated management to 50% of total rice harvested area of 11 Mha (FAOSTAT, 2017) in Bangladesh (assuming a mean sequestration rate of $0.32 \text{ t C ha}^{-1} \text{ yr}^{-1}$) would provide sequestration of approximately 1.8 Tg C yr^{-1} , which is close to the values predicted by Lal (2004) of $1.2\text{--}1.8 \text{ Tg C}$ by 2020, under adoption of recommended management practices in 6 Mha of croplands in Bangladesh.

4.3. Total GHG balance when also considering CH_4 and N_2O emissions

From the above sections, it appears that SOC sequestration can be achieved with management changes, and might deliver a significant contribution to the reduction of net GHG emissions by 2030. However, for the selected mitigation management- (integrated scenario for S1 and S2), increased CH_4 and N_2O emissions either partially, or totally negate the mitigation benefit provided by SOC sequestration. When integrated management is combined with AWD at S1, the overall GHG emissions decreased by $1.03 \text{ t CO}_2\text{-eq. ha}^{-1} \text{ yr}^{-1}$ (equivalent to $0.27 \text{ t Ceq. ha}^{-1} \text{ yr}^{-1}$). For S2, GHG emission reductions of $0.58 \text{ CO}_2\text{-eq. ha}^{-1} \text{ yr}^{-1}$ (equivalent to $0.16 \text{ t Ceq. ha}^{-1} \text{ yr}^{-1}$) were possible with mitigation options. Therefore, on average, the selected scenarios could reduce GHG emissions ($\text{CO}_2\text{-eq. ha}^{-1} \text{ yr}^{-1}$) by 12% per year of current total GHG emissions from agriculture in Bangladesh. Our findings show that it is essential to consider all GHGs together when trying to identify NAMAs for use in rice cropping systems in Bangladesh, since measures that may look attractive from a SOC sequestration perspective, might actually increase overall GHG emissions. However, given that N_2O and CH_4 emissions were estimated using IPCC tier 1 methods and region specific EFs in general, further studies should use advanced models for estimating non- CO_2 GHG emissions when sufficient calibration data become available.

In this study, the mitigation potential for SOC and GHGs were investigated considering nutrient, water, tillage and residue management. Due to data limitations, we could not fully assess the performance of the model at test sites simulations under tillage and residue management. Recently, Kader et al. (2016) studied SOC change under different management including tillage and residue management in a three year rice-wheat-mungbean crop rotation from BAU, Mymensingh and found a significant difference in SOC content in 0–5 cm between CT and RT, but no significant difference in SOC stock for the whole profile. Their study also observed no significant difference on SOC stock among reduced tillage, more residue return and the interaction of both. Although there were no data for CH_4 and N_2O emissions to calibrate DayCent, the effective mitigation in this study not only considers SOC sequestration, but also the GHG mitigation potential by reducing CH_4 and N_2O emissions. Based on model-based analysis with DayCent in China (the largest rice producing country), we concluded that the integrated scenario is an effective mitigation approach for mitigating net GHG balances.

5. Conclusions

An ecosystem model, DayCent, was tested with data from two long term experiments. The site tests revealed that SOC can increase in unfertilized paddy rice, and that this can only be simulated satisfactorily if additional C and N input are considered. Subsequent tests of various alternative management scenarios (individual practices and combinations) showed that SOC levels could be further increased without compromising yield. A scenario in which manure application rates were

increased had a large impact on SOC, but yield was compromised. Although a large portion of residue and cattle manure is used for household purposes, integrated management appears to be an effective method to increase SOC sequestration while maintaining yield in rice-based croplands in Bangladesh. Our results suggest that farmers could reduce current N fertilizer rates by 15% along with RT, increasing the proportion of residue return and applying manure to account for reduced mineral fertilizer. Additionally, farmers could save water in irrigated rice based cropping systems.

In terms of requirements for model improvement, our study suggests that parameters and algorithms describing nutrient accumulation in low input paddy soils may need to be improved. There is scope to improve the DayCent plant production sub-model to better simulate growth of non-crop plants during the cropping season, which contribute to SOC increases and act as an additional nutrient input. Although some aspects of carbon and N dynamics in some of the site test simulations did not fully match with the observations, the overall performance of DayCent was adequate, suggesting it is a useful model for estimating SOC sequestration potential in a paddy rice systems. The outcome can be improved in the future with further development of DayCent to represent different processes, and with improved data on soil properties at different depths, which are currently not available for Bangladesh. Based on our statistics, the model simulates measured SOC and yield reasonably. Uncertainties can be reduced in the future with further data collection and through use of optimization or Bayesian parameterization methods (Wang and Chen, 2013), but this is not currently possible with the limited data available in Bangladesh. Therefore we conclude that the model is reasonable for simulating carbon stock changes in this initial study to gain some insight into potentials for reducing emissions. Clearly, further study and refinement is needed if farmers and the government decide to pursue these mitigation options as part of policy program to reduce emissions, such as a program to contribute emission reductions to international efforts, such as the Paris Agreement. However, without initial studies such as our research here, programs will not evolve to investigate options further. Our findings could serve as an interim set of estimates for SOC stock changes until further evidence is gathered through field experimentation. After considering total GHG emissions using IPCC default and country-specific emission factors for CH_4 and N_2O , we can draw the following conclusions: 1) annualised SOC stocks of Bangladesh rice-based cropping systems can be increased by changing current management practices, with SOC increases greatest under integrated management of nutrient, more residue return, reduced tillage and water management rather than changes of single scenario; 2) increasing SOC stock under current mineral N fertilizer and continuous flooding conditions does not necessarily lead to mitigation, especially in double rice cropping systems, where CH_4 and N_2O emissions entirely offset the GHG mitigation provided by the SOC sink; and 3) water management is an effective mitigation scenario to explore as a NAMA for double rice ecosystems, which contributes to a reduction in total GHG emissions while maintaining yield.

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